# Reflectance-based calibration of SeaWiFS. I. Calibration coefficients

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We present a calibration approach for the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) based on the reflectance properties of the instrument's onboard diffuser. This technique uses SeaWiFS as a reflectometer, measuring the reflected solar irradiance from the Earth and from the onboard diffuser. Because the Sun is the common source of light for both measurements, the ratio of the SeaWiFS-measured radiances from the Earth and the diffuser provide the ratio for the reflectances of the two samples. The reflectance characterization of the onboard diffuser is the calibration reference for this approach. Knowledge of the value of the solar irradiance is not required for these measurements because it falls out of the ratio. Knowledge of the absolute calibration coefficient for the SeaWiFS measurements of each of the two samples is not required either. Instead, the result of the ratioing technique is based on the linearity of the instrument's response to the intensity of the input light. The calibration requires knowledge, however, of the reflectance of the onboard diffuser at the start of the SeaWiFS mission and the response of the instrument bands, in digital numbers, for measurements of the diffuser at that time. 

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## 1. Introduction

The Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) measures the upwelling Earth flux at wavelengths from 412 to 865 nm. Over this wavelength range, the flux comes from scattered sunlight. When the external light source is missing, such as on moonless nights, the Earth is essentially black in the visible and near infrared, except for anthropogenic illumination sources. Basically, the Earth behaves as a diffuse reflector for sunlight over these wavelengths, although the individual parts of this process can be quite complicated. This is the basis for the concept of remote sensing reflectance,[1,2] which is fundamental to measurements over the SeaWiFS wavelengths. For example, ocean chlorophyll is derived from a reflectance measurement, that is, from a measurement of scattered solar flux by phytoplankton after absorption by chlorophyll. In addition, properties of the land and atmosphere over these wavelengths are determined by remote sensing reflectance.

SeaWiFS measures the upwelling Earth flux as radiance because the Earth overfills the field of view of each SeaWiFS measurement. Thus SeaWiFS was calibrated in the laboratory with a large-aperture integrating sphere as a source of known radiance.[3] SeaWiFS measurements on orbit are tied directly to this laboratory source.[4] However, alternative calibration techniques by use of the Sun as the light source are possible. For example, the ground-based prelaunch calibration of SeaWiFS was performed outdoors,[5,6] where reflected sunlight from the SeaWiFS onboard diffuser provided the calibrated source of radiance. This calibration required knowledge of the reflecting properties of the SeaWiFS diffuser plus knowledge of the absolute value of the solar irradiance at the instrument's input aperture.

In addition, it is possible to calibrate SeaWiFS by use of the reflecting properties of the SeaWiFS diffuser without knowledge of the magnitude of the solar irradiance. This is the reflectance-based calibration of SeaWiFS. When this calibration is applied, SeaWiFS operates as a reflectometer, viewing the reflected solar flux from both the Earth and the onboard diffuser. Because the Sun is the common source of irradiance for both diffuse reflectors, the ratio of the two SeaWiFS measurements is also the ratio of the two reflectances. The reflectance-based

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calibration of SeaWiFS allows the direct determination of the remote sensing reflectance of the Earth, relative to the reflectance of the SeaWiFS onboard diffuser. It does not require knowledge of the absolute value of the flux from either the Sun or from an integrating sphere in the laboratory. However, the reflectance-based calibration does require the solar flux to be constant during the time between the two measurements in the ratio. This appears to be the case. Frölich[7] shows the solar constant to vary by approximately 0.2% over the course of a 22-year solar cycle. In addition, the reflectance-based calibration does not require knowledge of the calibrated radiances for the SeaWiFS measurements because the measurements are applied as a ratio. Instead, it is sufficient to know that the instrument output, in digital numbers (DNs), is a linear function of the input radiance as shown in Barnes *et al.*[8] Of course, it is also necessary to know other instrument characteristics, such as the relative spectral response.[4]

The reflectance-based calibration has three basic parts. The first is the laboratory characterization of the bidirectional reflectance distribution function (BRDF) of the onboard diffuser for the eight SeaWiFS bands. This is a system-level characterization of the diffuser and the diffuser assembly by use of an external light source and a pressed polytetrafluoroethylene (PTFE) diffuser as the calibration reference, as described in Section 3. The second part is the determination of changes, if any, in the diffuser BRDF from the time of the laboratory characterization to the start of the instrument's on-orbit operations. This is described in Section 4. The final part is the determination of diffuser changes since the start of on-orbit operations. This is described in Section 5. In addition, in Section 5 we describe the calculation of the eight instrument outputs, in DNs, at the start of the SeaWiFS mission. These values are an integral part of the reflectance-based calibration coefficients (see Section 7). In Sections 4 and 5 we use both system-level characterizations of the diffuser–diffuser assembly, with the Sun providing the input irradiance and the SeaWiFS instrument measuring the output radiance.

## 8. Concluding Remarks

The SeaWiFS transfer-to-orbit experiment[12] was based on a prediction of the DNs from the instrument at the time of the insertion of the instrument into orbit. In that experiment, there were minimal corrections to the DNs from orbit. There were no corrections for the temperatures of the focal planes or for the yaw angle of the on-orbit measurements. These corrections were included in the uncertainties for that experiment, and they were considered small with respect to the uncertainty in the atmospheric transmittance for the ground measurements.[12] The measurement results for $\mathrm{DN}_D(t_0)$ in Table 3 include the on-orbit instrumental effects. As such, they provide an update to the results of the transfer-to-orbit experiment. In addition, the updated comparison of the predicted values for the start of the SeaWiFS mission and of their measured counterparts for the same time is shown in Table 4.

For the transfer-to-orbit experiment, the effect of the Earth–Sun distance was applied to the predicted digital numbers $\mathrm{DN}_P$ [see Eq. (14) of Barnes *et al.*[12]]. This was done to eliminate the need for this correction to the measured DNs from orbit. Thus, for the transfer-to-orbit experiment,[12] the measurements from orbit were reported without the Earth–Sun distance correction. Because the Earth–Sun distance was 1.015 AU at the start of the SeaWiFS mission on orbit, the predicted DNs for the transfer-to-orbit experiment ($\mathrm{DN}_P$) were reduced by 3%. However, the values for $\mathrm{DN}_D(t_0)$ in Tables 3 and 4 have a correction for the Earth–Sun distance included in their calculation (see Section 5). They are corrected to an Earth–Sun distance of 1 AU. Thus the 3% correction to $\mathrm{DN}_P$ in the transfer-to-orbit calculations becomes redundant here. This is the reason for the $D_{\mathrm{ES}}{}^2(t_0)$ factor in Table 4 and the 3% increase in the values for $\mathrm{DN}_{\mathrm{CORR}}$ relative to $\mathrm{DN}_P$.

The results in Table 4 show the measured DNs to average 0.6% lower than the predicted values with a standard deviation of 1.0%. For the transfer-to-orbit experiment, the measured DNs averaged 0.8% higher than the predicted values with a standard deviation of 0.9%.[12] In both cases, the results fall within the 3% uncertainty of the experiment. Thus the results of the reflectance calibration of SeaWiFS presented here do not change the basic results of the transfer-to-orbit experiment from Barnes *et al.*[12]

Other Earth-observing satellite sensors use their solar diffusers as the basis for the radiance-based calibration of their measurements.[24,25] This type of calibration requires a knowledge of the characterization of the diffuser plus knowledge of the magnitude of the solar spectral irradiance to provide a reference spectral radiance from the surface of the diffuser. Thus, with use of a solar irradiance model, it is also possible to use the reflectance-based calibration of SeaWiFS as the basis for a radiance-based calibration of the instrument at the start of on-orbit operations. In addition, there are three other prelaunch radiance-based calibrations of SeaWiFS. The first is based on measurements of an integrating sphere by the instrument manufacturer in 1993[26]; the second is based on measurements of a different integrating sphere four months before the launch of SeaWiFS in 1997[3]; and the third is the prelaunch SeaWiFS solar radiation-based calibration[5,6] performed outdoors at the instrument manufacturer's facility with the Sun used as the light source. For SeaWiFS, the calibration in 1997, just before launch, is the basis for the instrument's on-orbit calibration.[4] The internal consistency of these four radiance-based calibration techniques is discussed in the companion paper.[27]